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# BINSTAR, A NEW TOOL FOR THE EVOLUTION OF LOW- AND INTERMEDIATE-MASS BINARY STARS

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**Abstract.** The evolution of stellar components in binary systems may be strongly influenced by their companion, for example, via Roche lobe overflow. This is particularly true for short period systems that can undergo significant mass transfer. In this paper, we present the new binary star evolution code for interacting binaries, Binstar. This code has been designed to consistently follow the structure and evolution of low- and intermediate-mass stars affected by mass and angular momentum transfer and spin-down mechanisms such as magnetic braking or the formation of a star-disc boundary layer. We applied Binstar to the study of an Algol system consisting of 6 + 3.6 $M_\odot$ stellar components with initial period $P_{init}$ = 2.5 days. We find that the gainer can maintain a spin velocity below the critical Keplerian value if magnetic braking with a strong magnetic field (of about 3kG) is applied, or if star-disc boundary layer interactions is considered. However, tides only cannot prevent the gainer from reaching critical rotation during the accretion phase.

Keywords: Stars: evolution, Stars: binaries: general, Accretion: accretion disks, Stars: magnetic field

## 1 Introduction

The study of binary systems is relevant to many astrophysical domains. Binary stars allow a precise determination of stellar masses (the key parameter for stellar evolution) and are progenitors of many other objects for example Type Ia supernovæ, X-ray bursts and probably $\gamma$-ray bursts.

Previous numerical simulations have provided a broad understanding of short-period binaries. Although some features, for example mass transfer in circular orbits or non-conservative evolution, have been extensively studied, there is no simulation that follows all angular momentum contributions (stellar and orbital) coupled with the treatment of the star disc boundary layer (hereafter star-disc interaction). It is well-known that mass transfer is associated with exchange of angular momentum, resulting in the spin-up of the gainer star. Packet (1981) showed that so much angular momentum is transferred that the gainer's surface velocity can reach the critical Keplerian velocity $v_{*,\mathrm{surf}} = \sqrt{GM_*/R_*}$ (hereafter critically rotating accretors). Up to now, no evolutionary code consistently handles such cases. In this paper, we describe the main properties of the new code Binstar dedicated to the study of low- and intermediate-mass binary systems. We analyse the torques arising from star-disc interaction and magnetic fields in order to better understand the accretion of angular momentum in Algol systems.

## 2 The Binstar code

Binstar is an extension of the 1-dimensional stellar evolution code Starevol, that handles the simultaneous calculation of the binary orbital parameters (separation and eccentricity) and the two stellar components. The stellar input physics is the same as described in Siess (2006).

Binstar follows the evolution of the system angular momentum ($J_\Sigma$) which is the sum of the stellar (subscript 'd' for the donor and 'g' for the gainer) and orbital components i.e.:

$$J_\Sigma = J_\mathrm{d} + J_\mathrm{g} + J_\mathrm{orb}. \tag{2.1}$$

The stellar torques $\dot{J}_{\mathrm{d,g}}$ applied on each star come from tidal, mass transfers or magnetic field interactions and will be described below. A Henyey method is used to solve simultaneously the structure of the two stars and the binary parameters (separation, eccentricity), as described in Siess et al. (2013).

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**Mass loss and associated torques** There are two modes of mass loss from a star: via winds or via Roche lobe overflow (hereafter RLOF). Winds carry away a fraction of the stellar spin angular momentum so for star 'i' (i = d or g) the resulting stellar torque is:

$$\dot{J}^{\rm wind}_{\rm loss,i} = -\frac{2}{3}|\dot{M}^{\rm wind}_{\rm loss,i}|\Omega_{\rm i}R_{\rm i}^2, \tag{2.2}$$

where $\dot{M}^{\rm wind}_{\rm loss,i}$ is the wind mass loss rate and $\Omega_{\rm i}$ the stellar spin angular velocity. In this study, we assume solid rotation. During the mass transfer phase, the mass loss rate $\dot{M}^{\rm RLOF}_{\rm loss,d}$ due to RLOF is computed following the formalism given by Kolb & Ritter (1990) which differentiates between the optically thin or optically thick regime depending on the location of the Roche lobe radius inside the star. The matter leaving the star carries the donor's surface specific angular momentum, resulting in a torque for the donor:

$$\dot{J}^{\rm RLOF}_{\rm loss,d} = -|\dot{M}^{\rm RLOF}_{\rm loss,d}|\Omega_{\rm d}R_{\rm d}^2. \tag{2.3}$$

**Mass accretion and associated torques** In case of RLOF, only a fraction $\beta$ of the matter lost from the donor may be accreted by the gainer because of the formation of a hot-spot or a circumstellar disc or ring, for example. A system is said to be conservative when the total mass and the total angular momentum (stars + orbit) are conserved ($\beta = 1$). The matter that leaves the donor at the first Lagrangian point may either directly impact the star or form an accretion disc. To determine the specific angular momentum accreted on the gainer as well as the accretion mode (direct impact or disc accretion), we compute the ballistic motion of a test particle in the gainer potential well (Flannery 1975). In case of direct impact, the resulting torque is:

$$\dot{J}^{\rm RLOF}_{\rm acc,g} = \beta|\dot{M}^{\rm RLOF}_{\rm loss,g}|\,||\vec{R}\wedge\vec{v}||, \tag{2.4}$$

where $\vec{R}$ is the radius vector between the centre of the gainer star and the particle at the point of impact, and $\vec{v}$ is the stream velocity at that location. On the other hand, if accretion occurs via a disc, the accreted specific angular momentum is equal to the Keplerian value at the surface of the star and the torque is:

$$\dot{J}^{\rm RLOF}_{\rm acc,disc} = \beta|\dot{M}^{\rm RLOF}_{\rm loss,g}|\sqrt{GM_{\rm g}R_{\rm g}}. \tag{2.5}$$

Finally, we note that part of the wind ejected from a star can be accreted by the companion (Bondi & Hoyle 1944). The accreted material carries a fraction $f_{J_{acc}}$ of the surface angular momentum of the star that expelled the wind and the torque on the wind accreting star 'i' (companion star '3-i') is:

$$\dot{J}^{\rm wind}_{\rm acc,i} = \frac{2}{3}f_{J_{\rm acc}}\dot{M}^{\rm BH}_{\rm i}\Omega_{3-{\rm i}}R^2_{3-{\rm i}}, \tag{2.6}$$

where $\dot{M}^{\rm BH}_{\rm i}$ is the Bondi-Hoyle mass accretion rate.

**Magnetic wind braking** If the star possesses a magnetic field, the mass ejected in the wind follows the open magnetic field lines until it reaches the Alfvèn surface (Weber & Davis 1967). At this point, the matter freely escapes the system with a higher specific angular momentum than the one available at the stellar surface. Because of this level-arm effect, the star spins down more efficiently. To determine the torque due to magnetic wind braking, we use (Dervişoğlu et al. 2010):

$$\dot{J}_W = -[(-\dot{M}_{\rm loss})^{(4n-9)}B_{\rm i}^8(2GM_{\rm i})^{-2}R_{\rm i}^{8n}]^{1/(4n-5)}\Omega_{\rm i}, \tag{2.7}$$

where $n$ is a parameter characterizing the geometry of the magnetic field and $B_{\rm i}$ is the stellar magnetic field strength. It is a reasonable approximation to assume a dipolar magnetic field with $n = 3$ (Livio & Pringle 1992). This torque depends on the mass loss rate $\dot{M}_{\rm loss}$ (mostly winds), the stellar spin $\Omega_{\rm i}$ and the magnetic field strength $B_{\rm i}$. In our models, $B_{\rm i}$ is a free parameter and the wind mass loss rates follow standard prescriptions.

**Magnetic Disc locking** The dipolar stellar magnetic field anchors into the accretion disc that may form around the gainer. Since the disc does not co-rotate with the star, the stellar magnetic field lines are twisted, creating a toroidal magnetic field component. In turn, this toroidal magnetic field generates a torque on the star. In the best case, when all the disc contributes to spin down the star, the torque writes (Dervişoğlu et al. 2010):

$$\dot{J}_{\rm disc\ locking} = -\frac{\mu^2 \Omega_{\rm i}^2}{3GM_{\rm i}}. \tag{2.8}$$

The torque depends on the stellar spin, which is not a parameter but fixed by the evolution of the system, and on the magnetic field strength through $\mu = B_{\rm i} R_{\rm i}^3$.

**Tidal effects** Tides are responsible for the synchronisation of the stellar spin with the orbital period. The efficiency of tidal torques increases when the orbital separation decreases. Some semi-detached binaries such as Algols are short period systems (from hours to tens of days). Therefore, we expect tides to play an important role in such systems. The tidal prescriptions of Zahn (1977) and the refinement for convective stars in short period binaries provided by Zahn (1989) are implemented in BINSTAR (for details, see Siess et al. (2013)).

**Accretion disc and star-disc boundary layer** BINSTAR includes the treatment of star-disc interactions. We apply the model of Paczynski (1991) which determines the accretion disc structure by assuming that the star and the disc are only one fluid. In the disc, advection of matter is driven by the outward transport of angular momentum by viscosity. By treating the star-disc boundary layer with a one fluid model, the same mechanism occurs at the surface of a critically rotating star. Viscosity processes remove angular momentum from the star, keeping it at a critical rotation rate but not exceeding it. This process allows the star to accrete large amounts of mass while giving angular momentum back to the disc. The extra stellar spin angular momentum transferred to the disc allows it to spread. Up to a certain radius, tidal forces disrupt the disc (Lin & Papaloizou 1979), and the angular momentum is given back to the orbit. For our models, we assume a disc to form as soon as the gainer reaches spin angular velocity of 0.8 the Keplerian value.

## 3 The case of critically rotating accretors in Algols

During the evolution of Algols, mass and angular momentum are transferred from the donor to the gainer via RLOF. The mass transfer rate can reach values as high as $10^{-4}$ $M_\odot$ yr$^{-1}$. However, only a few percent (0.12 $M_\odot$ over more than 5 $M_\odot$ transferred during the total mass transfer phase for our studied system) is sufficient to spin the gainer up to its critical rotation if no spin-down mechanism is invoked. Several scenarios have been investigated to overcome this problem. We discuss here the impact of tides, magnetic field braking and accretion via star-disc boundary layer interaction.

The tidal synchronisation time-scale is much longer than the time-scale for mass transfer ($M_{\rm g}/\dot{M}_{\rm acc,g}^{\rm RLOF}$), hence tides are inefficient to spin down the star. However, tides are likely to have an important role in spinning down the gainer star after the mass transfer episode because the tidal time-scale becomes short compared to the binary evolutionary time-scale. Also, after mass transfer stops, we do not expect the boundary layer and disc-locking mechanism to apply any longer.

The left panel of Fig. 1 shows the time evolution of the surface angular velocity (normalized to the critical velocity) of our system for different magnetic field strengths compared to a standard case (termed 'Free-rotation') where the evolution of the rotational velocity is not constrained. Only a strong magnetic field of around 3 kG can prevent the gainer from reaching the critical Keplerian velocity.

Irrespective of how much matter is transferred, the boundary layer mechanism keeps the star at the critical velocity. As the specific angular momentum accreted differs between spin-down mechanisms, the stellar spin angular momentum and in turn the orbital angular momentum change, subsequently affecting the separation of the system. The right panel of Fig. 1 displays the evolution of the separation for three models ('Free-rotation', magnetic field (3 kG), star disc boundary layer) for our considered system. We clearly see that the spin-down mechanism has a large impact on the binary separation, producing shorter period systems for the boundary-layer model. This variation will then impact on the subsequent long term evolution of the binary system, leading to different objects, for example detached binaries or contact systems.

## 4 Conclusions

In this study, we performed the first binary evolution that consistently takes into account the torques arising from magnetic field and star-disc interactions in an Algol system with a critically rotating accretor. Strong magnetic fields (of about 3 kG for our standard 3 + 6 $M_\odot$ case with $P_{\rm init}$ = 2.5 days) and star-disc interactions

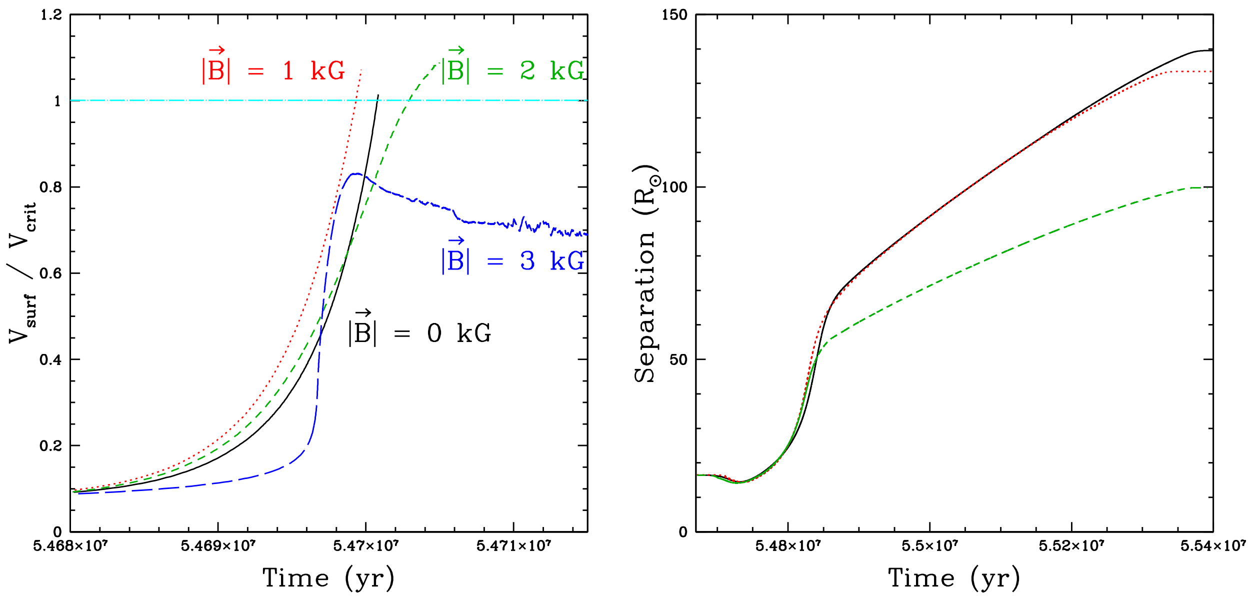


**Fig. 1. Left:** Evolution of the surface velocity (gainer only, normalized to the critical velocity) for different magnetic field strengths for a 6 + 3.6 $M_\odot$ system with initial period $P_{init}$ = 2.5 days. Solid black line: $|\vec{B}_s|$ = 0 kG; dotted red line: $|\vec{B}_s|$ = 1 kG; dashed green line: $|\vec{B}_s|$ = 2 kG; long-dashed blue line: $|\vec{B}_s|$ = 3 kG. The dot-dashed magenta straight line represents the critical angular rotation of the star. All simulations are stopped when $v_{surf} \approx v_{crit}$. Only the simulation with a strong enough magnetic field avoids the critical rotation. **Right:** Evolution of the binary separation for three different configurations for the same system. Solid black line: rotation not treated ('Free-rotation'); dotted red line: magnetic field 3 kG; dashed green line: star-disc boundary layer treatment. The final separation (after the end of the mass transfer phase at $t \approx 5.535 \times 10^7$ yr) strongly depends on the treatment of the braking mechanism. In the 'Free-rotation' model, the final separation is larger than in a system accounting for rotation.

can sufficiently spin down the accretor to avoid any super-critical rotational velocities. On the other hand, tides are not efficient enough, although they are not excluded to be at work to slow down the gainer after the mass transfer phase. We show that the overall evolution of the system and especially the final separation depends sensitively on the spin-down mechanism which may lead to different subsequent evolution of the binary system.

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